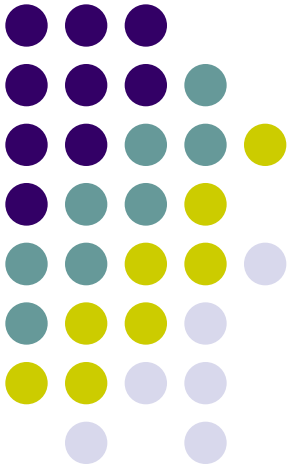
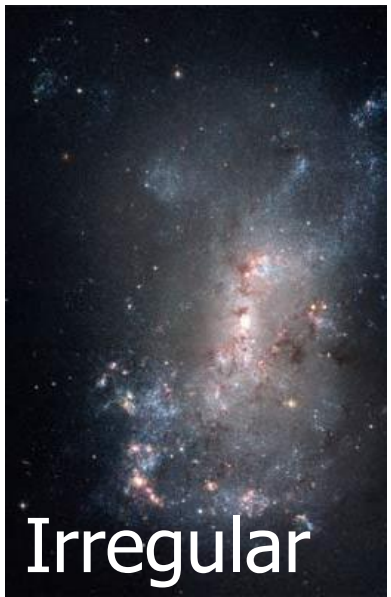
Universe of Galaxies

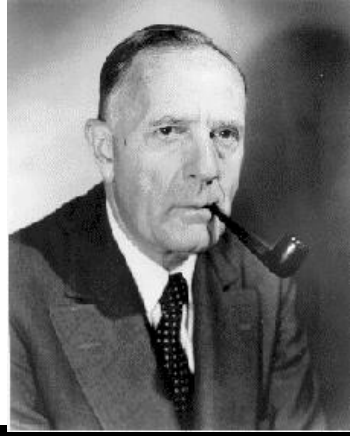


The World of Galaxies

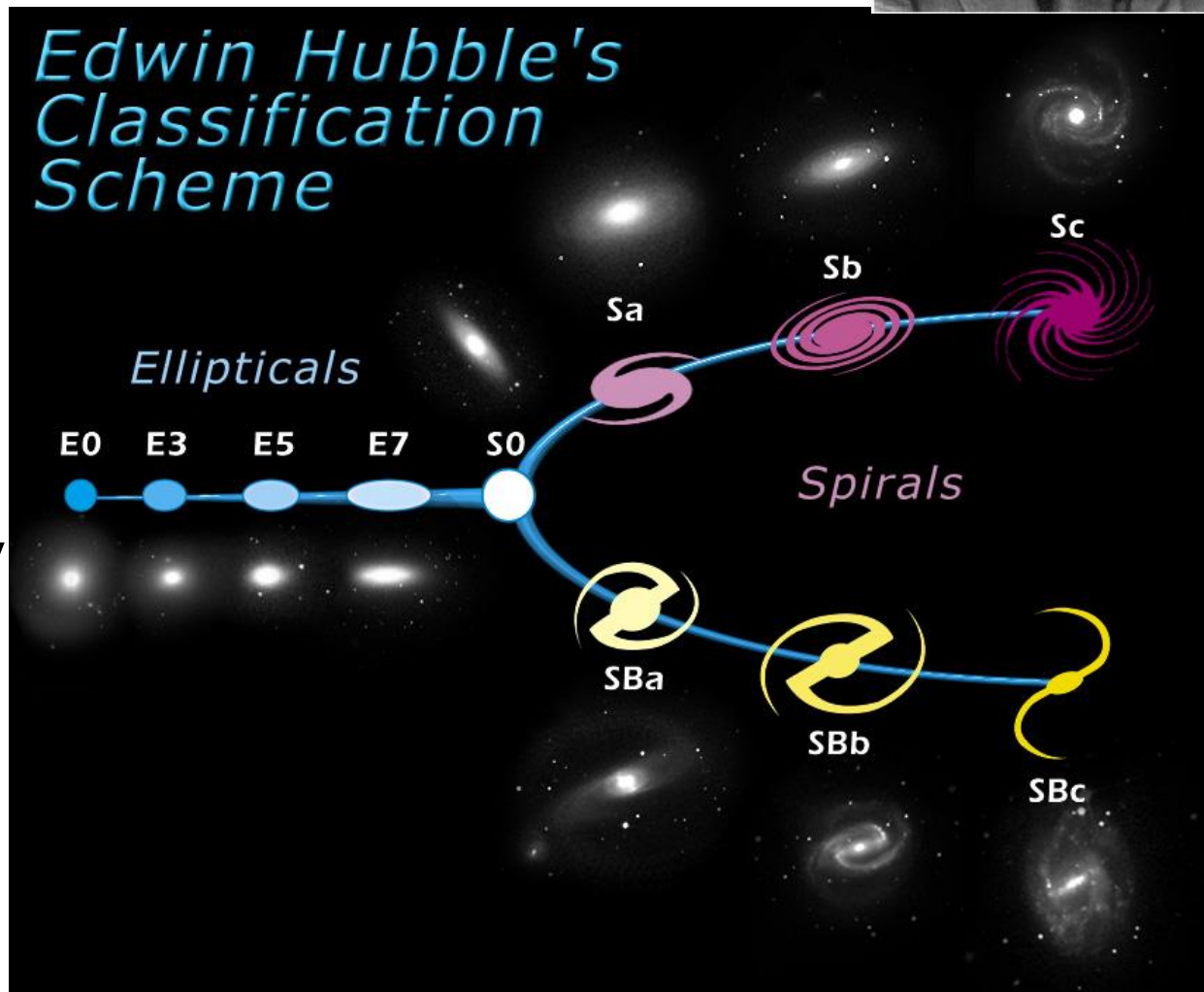
- Galaxies come in three main types:
  - Spirals (like the Milky Way and Andromeda)
  - Ellipticals (they mostly live in large clusters)
  - Irregular (often small, look like mess)



Hubble's Classification



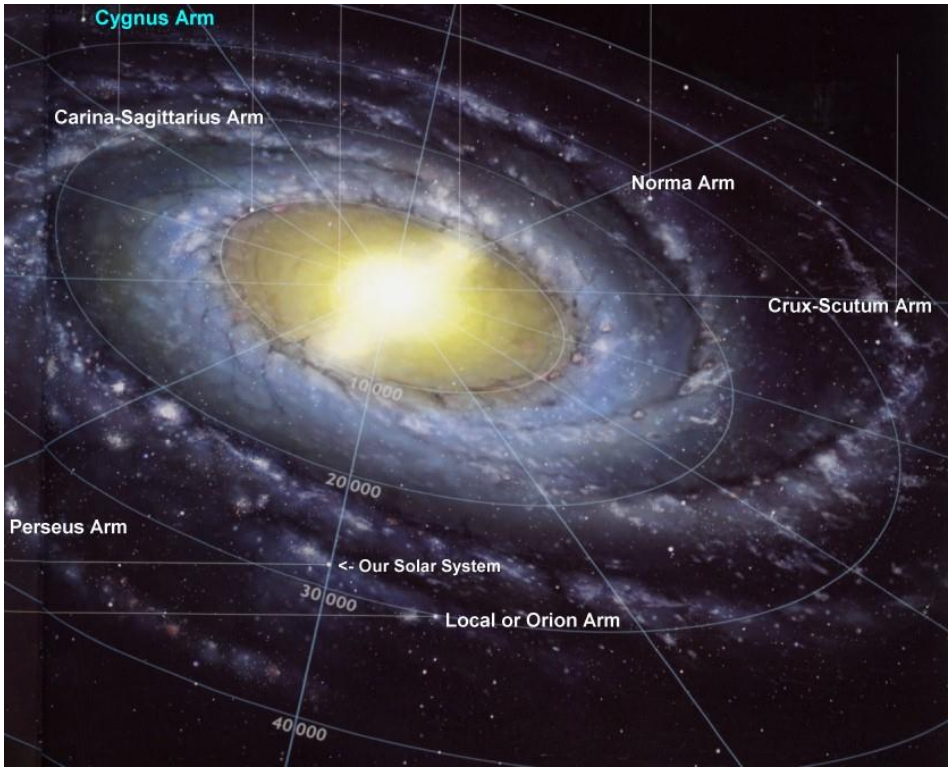
- Edwin Hubble developed a classification scheme that is still in use.
- Many spirals have ***bars*** – the Milky Way has too.



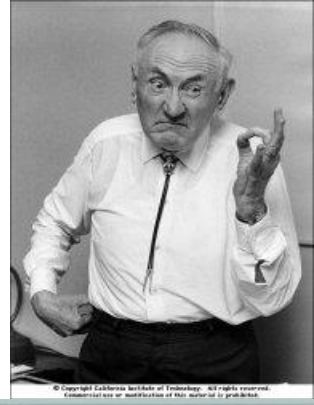
The Milky Way Bars

A bar ***in*** the Milky Way

A bar ***of*** the Milky Way

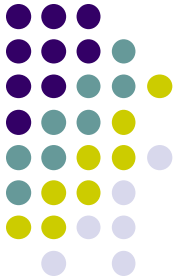


Fritz Zwicky (1898 – 1974)



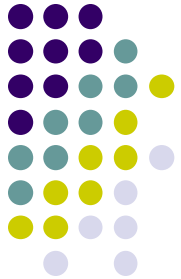
- Swiss immigrant to the US.
- He was a Professor of Astronomy at Caltech, and a research director/consultant for Aerojet Engineering Corporation.
- Made large contributions in jet engine design.
- In 1933, while studying motions of galaxies in the Coma galaxy cluster, he concluded that all ***visible matter*** was not enough to explain the motions. He postulated the existence of the invisible ***dark matter***. He was ridiculed.

Visible Matter



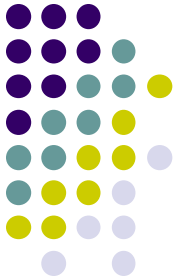
- What we see from the sky is light - light from stars and hot gas. It is more-or-less straightforward to count how much mass is there in the form of stars and hot gas.
- In order to do that we need to translate light into mass. This is done by measuring the so called ***mass-to-light*** ratio, M/L .
- It is measured in *solar units*.

Solar Units



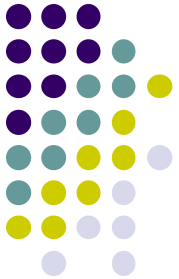
- Astronomers often deal with *astronomical* numbers. Hence, they often use special measurement units.
- We already met a unit of distance, *parsec* (pc, kpc, Mpc).
- Masses in astronomy most commonly measured is solar masses, $M_\odot = 2 \times 10^{30}$ kg.
- Luminosities (= power) are measured in solar luminosities, $L_\odot = 4 \times 10^{26}$ Watts.

Question



- The mass-to-light ratio of the Sun is
  A. 0
  B. 1
  C. 10

Measuring Masses



- In a rotating system, centrifugal force balances gravity:

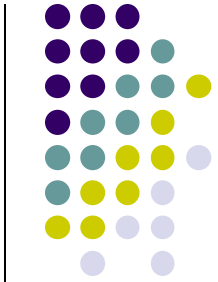
$$M\frac{V_{\rm rot}^2}{R} = \frac{GM^2}{R^2}$$

- In an elliptical system, the pressure of random motions of stars balances gravity:

$$M\frac{V_{\rm rand}^2}{R} = \frac{GM^2}{R^2}$$

- This is simply the third law of Kepler!

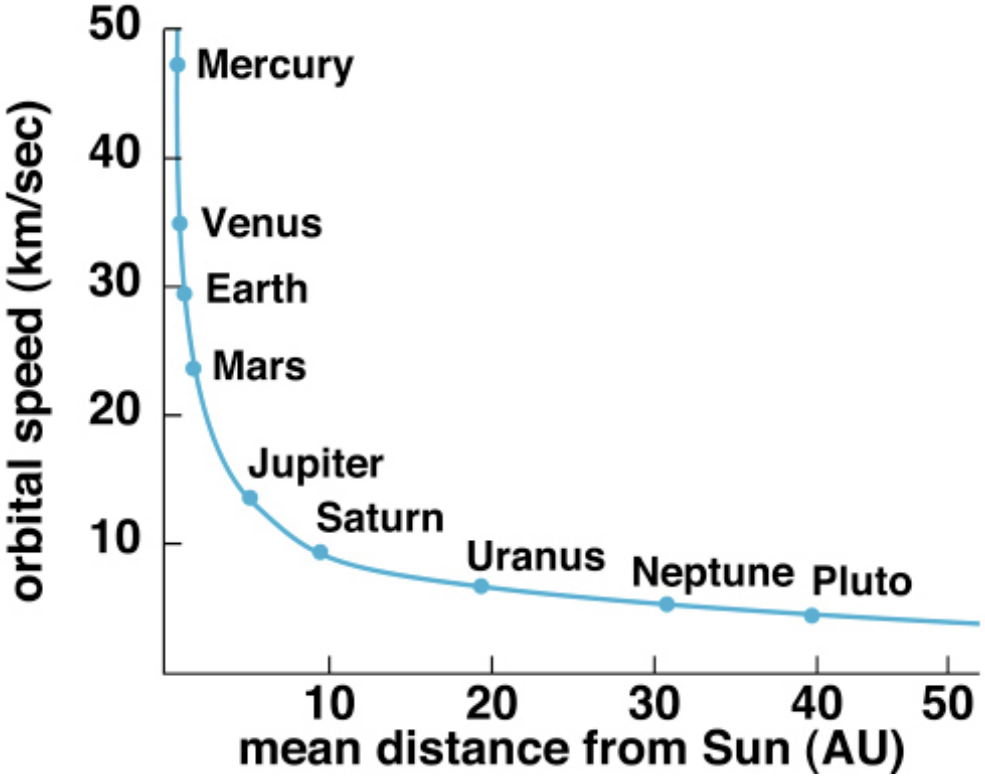
Thank You, Kepler!



- Cancel one M: $$\frac{V^2}{R} = \frac{GM}{R^2}$$
- Re-arrange: $$\frac{RV^2}{G} = M$$
- A miracle! We got the mass of something we cannot put on a scale or even reach!

Rotation Curve

- Rotation curve plots orbital velocities of rotating bodies versus their distance from the center.
- A rotation curve for the Solar system has a definite shape – ***Keplerian rotation curve***.

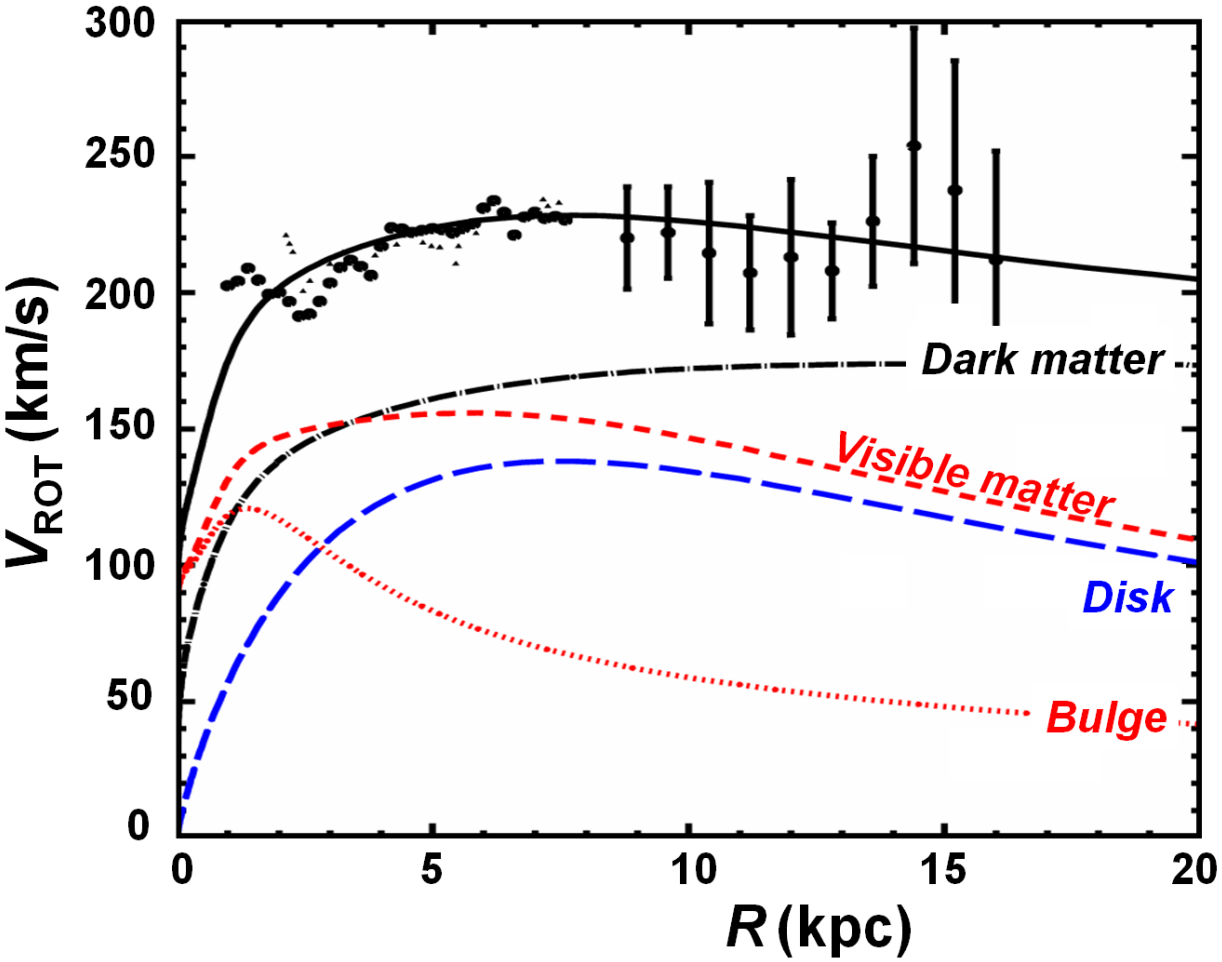


Rotation Curves in Spiral Galaxies

- In 1959, Louise Volders found that spiral galaxy M33 rotates faster than it should.
- In 1975, Vera Rubin presented her measurements of rotation of several spiral galaxies. Rotation curves were “flat”, very different from Keplerian.
- Using these observations, Jerry Ostriker & Jim Peebles estimated the masses of typical spiral galaxies. These masses were 10 times higher than the total mass of the disk, the bulge, and the stellar halo.

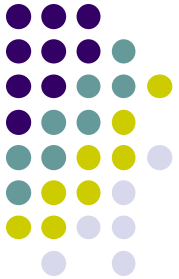
Galactic Rotation Curve

- In the Milky Way stars rotate way too fast for its mass – it must contain invisible ***dark matter***!



From the work of Anatoly Klypin, HongSheng Zhao, & Rachel Somerville.

Galactic Dark Matter

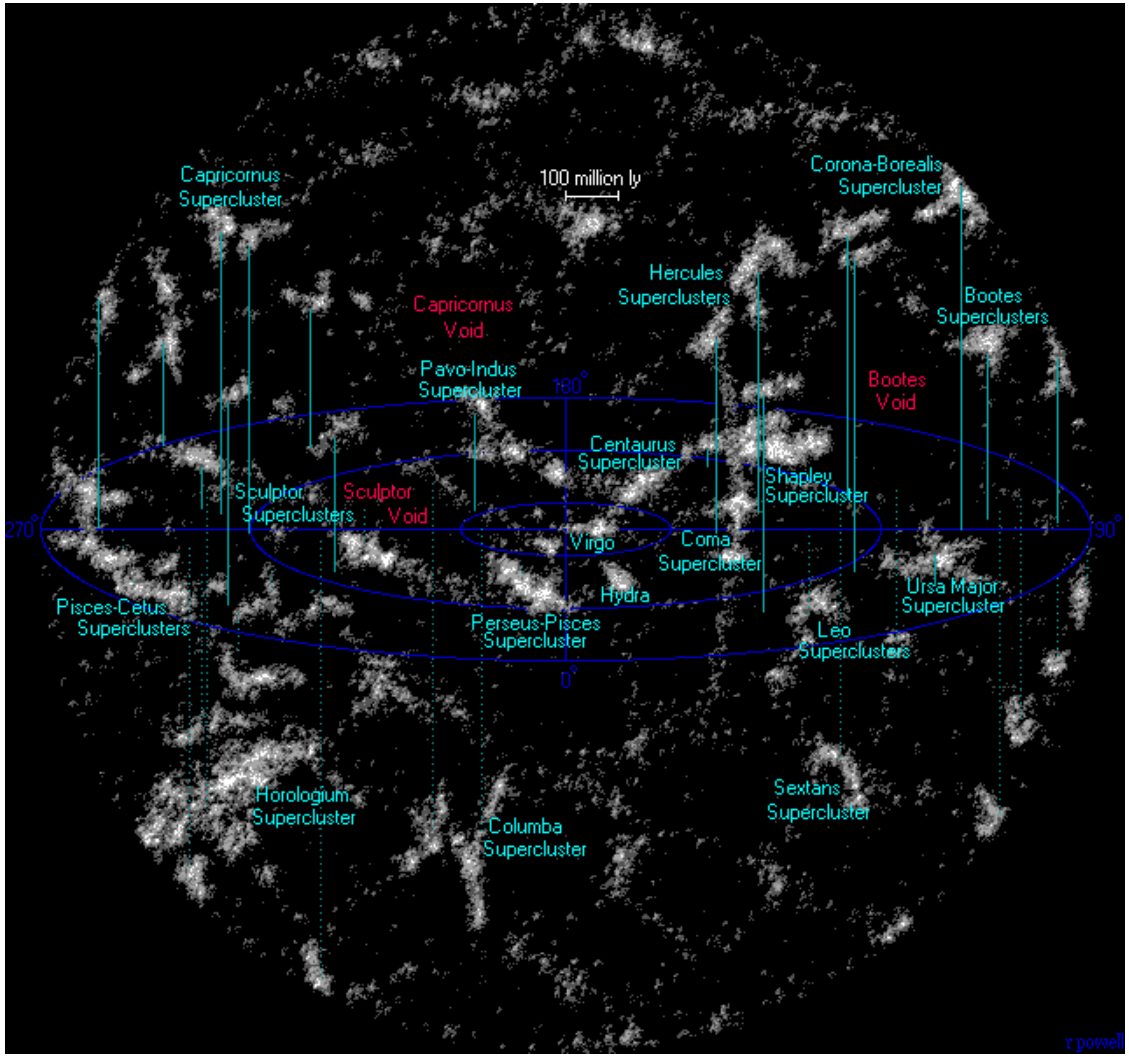


- Possible sources of galactic dark matter:
  - cold gas.
  - stellar “cinders”: white dwarfs, neutron stars, black holes.
  - brown dwarfs.
  - jupiters.
  - “non-baryonic” (or “particle”) dark matter.
- The mass-to-light ratios of spiral galaxies can be explained by the baryonic dark matter. It is only when we move to the galactic halos, we discover evidence for the non-baryonic dark matter.

MACHOs

- In about 1992 a MACHO (MAssive Compact Halo Object) collaboration formed which used ***gravitational lensing*** to detect compact massive objects in the halo of our Galaxy.
- After seven years of observations, they concluded that about 20% of the halo is made out of MACHOs with an average mass of about one half solar. This is suspiciously close to the average mass of a white dwarf, but not enough to account for all of dark matter.

Galaxies In Space

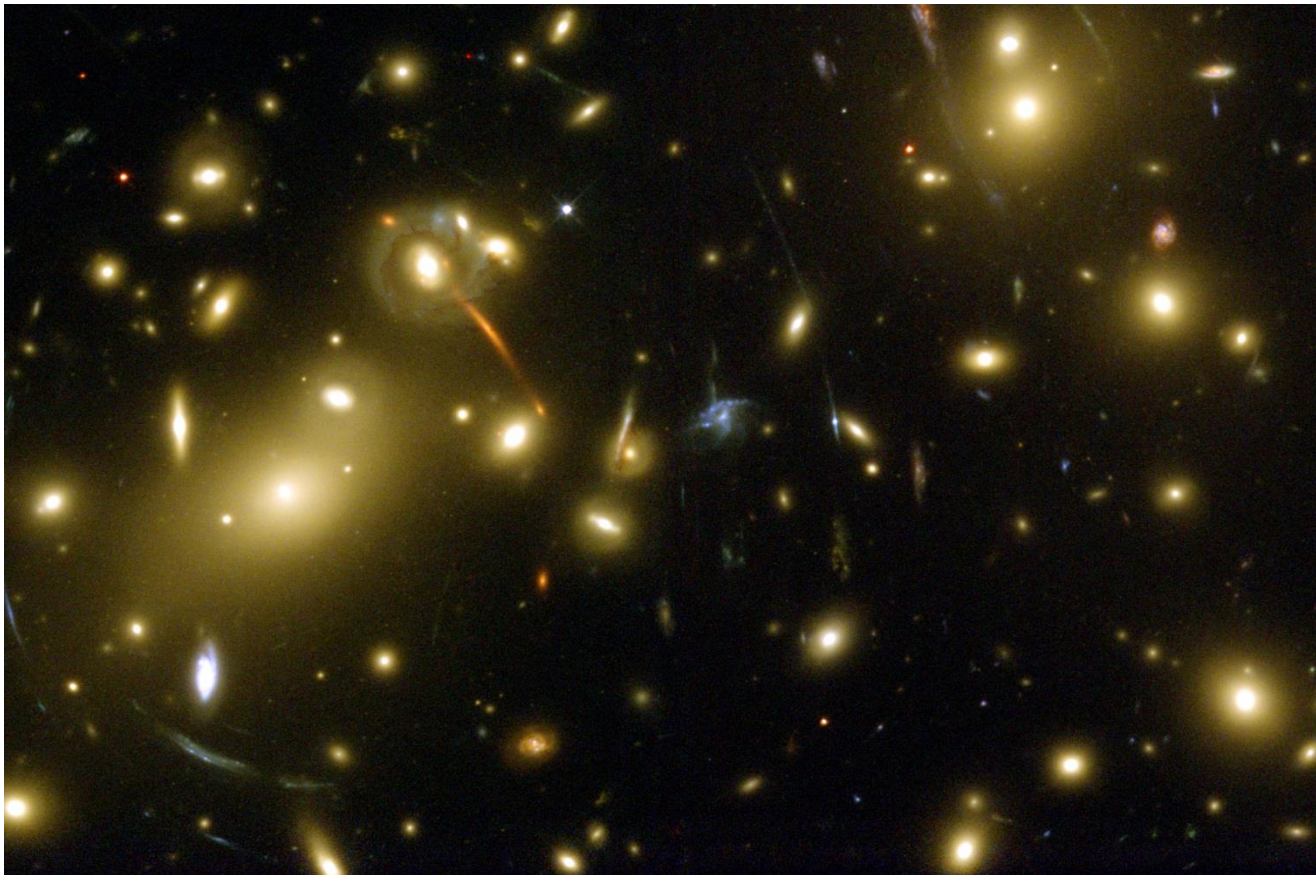


Galaxies In Space

- Galaxies are like people – they don’t like to live alone.
- Many of them live in small villages and hamlets, like the Milky Way and Andromeda galaxies.
- Most of them live in mid-size towns called “galaxy groups”.
- But there are also huge cities – metropolia of galaxy world, called “galaxy clusters”.

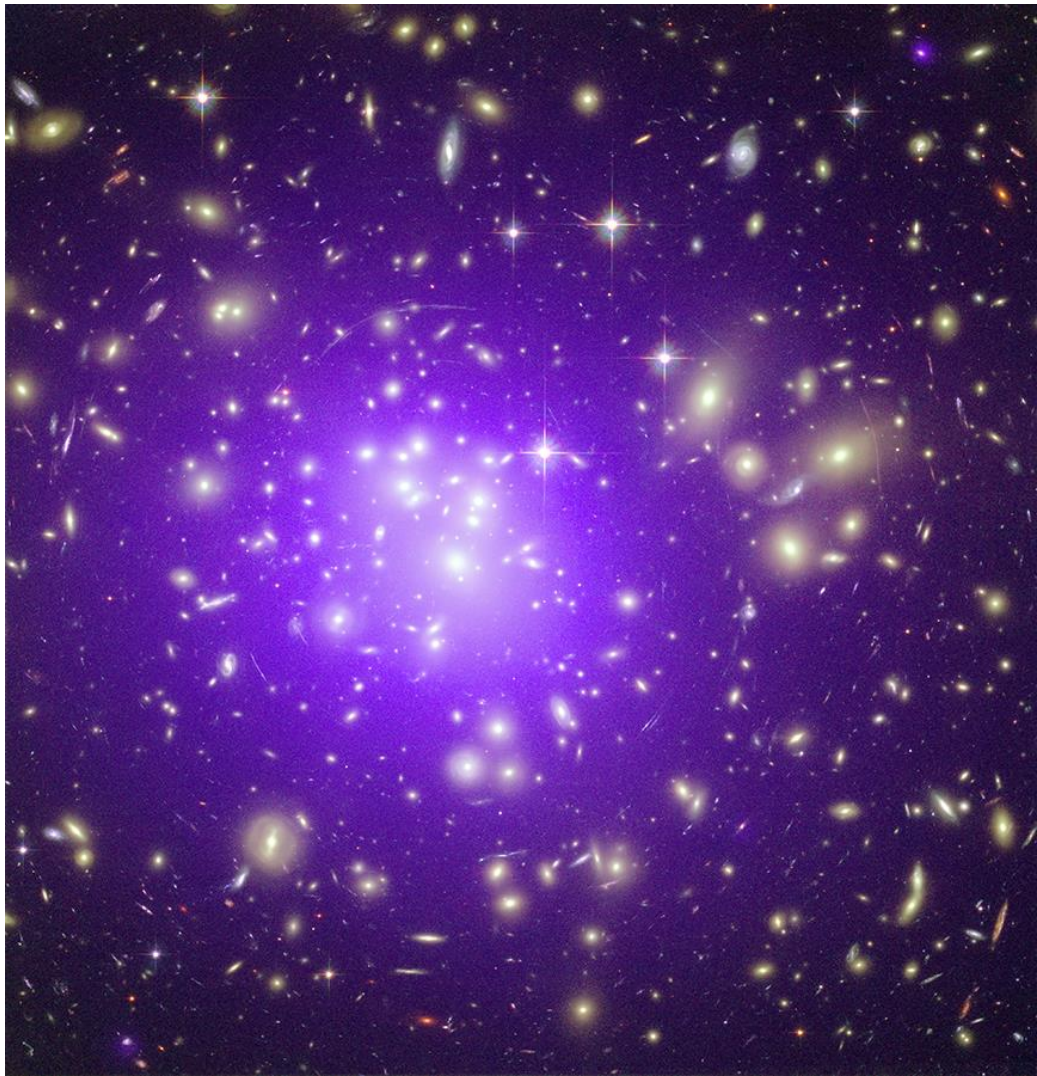
Clusters Of Galaxies

- Clusters are the biggest objects in this universe – there is nothing bigger one can call “an object”.

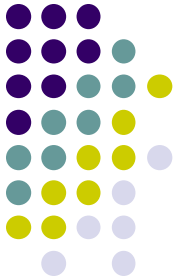


Clusters Of Galaxies

- Their gravity is so strong, it sucks in a lot of gas from outside, and make that gas shine in X-rays.
- Shining hot gas is simple – easy to measure its mass.



Measuring Masses Again



- In a rotating system, centrifugal force balances gravity:

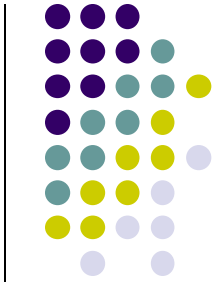
$$M\frac{V_{\rm rot}^2}{R} = \frac{GM^2}{R^2}$$

- In a cluster, the pressure of hot gas balances gravity:

$$M\frac{V_{\rm gas}^2}{R} = \frac{GM^2}{R}$$

- Wait! Pressure depends on temperature – where is temperature here?

Measuring Masses Again

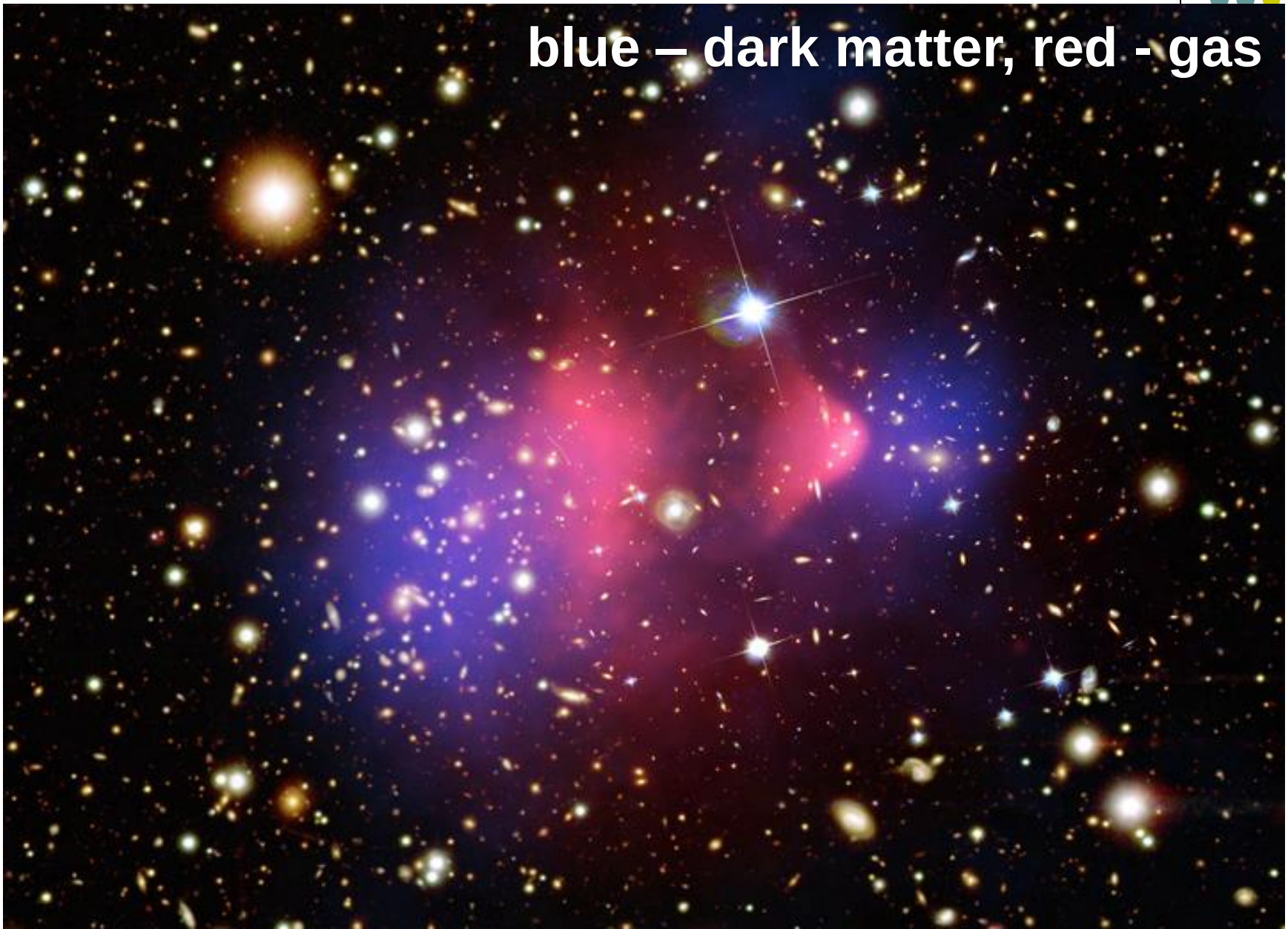


- At the end, it is the Kepler's 3rd law again – can't hide from it anywhere!
- From using it me know – clusters contains 6 times more mass than the total mass of its stars and gas (and gas beats stars 5 to 1).
- Such measurements are the 2nd strongest existing evidence for the existence of non-baryonic dark matter.

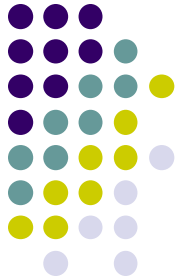
“Bullet” Cluster

- Most clusters are peaceful loners, but sometimes they do collide with each other.
- In such collisions everything gets whacked – gas flies one way, stars (and dark matter) fly the other way.
- “Bullet” cluster is one of the most spectacular collisions of that sort – and **the best evidence** for the existence of the dark matter we have today!

“Bullet” Cluster



Conclusion



- Whether you like it or not, most of matter in the universe is made out of non-baryonic dark matter.
- If you think this is bizarre, wait until Friday.